Stand Alone Battery Thermal Management System

2015 DOE Vehicle Technologies Program Review

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Project ID: ES135

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Overview

Timeline	Barriers
•Start: October 1, 2011 •End: September 30, 2015* •Percent Complete: 80% * Includes 1 year no cost extension	• Barriers Addressed - Cost - Reliability - Life
Budget	**Partners**
•Total Budget - Government Share: $2,610,555 - Contractor Share: $693,924 •Government Funding Received: - FY11: $37,981 - FY12: $478,710 - FY13: $314,287 - FY14: $281,016 • Government Funding for FY15 - $437,701	• National Renewable Energy Laboratory Cell Testing, Simulation Support, Validation Testing • FCA US LLC System Targets, Concept Approval, Bench Test Support

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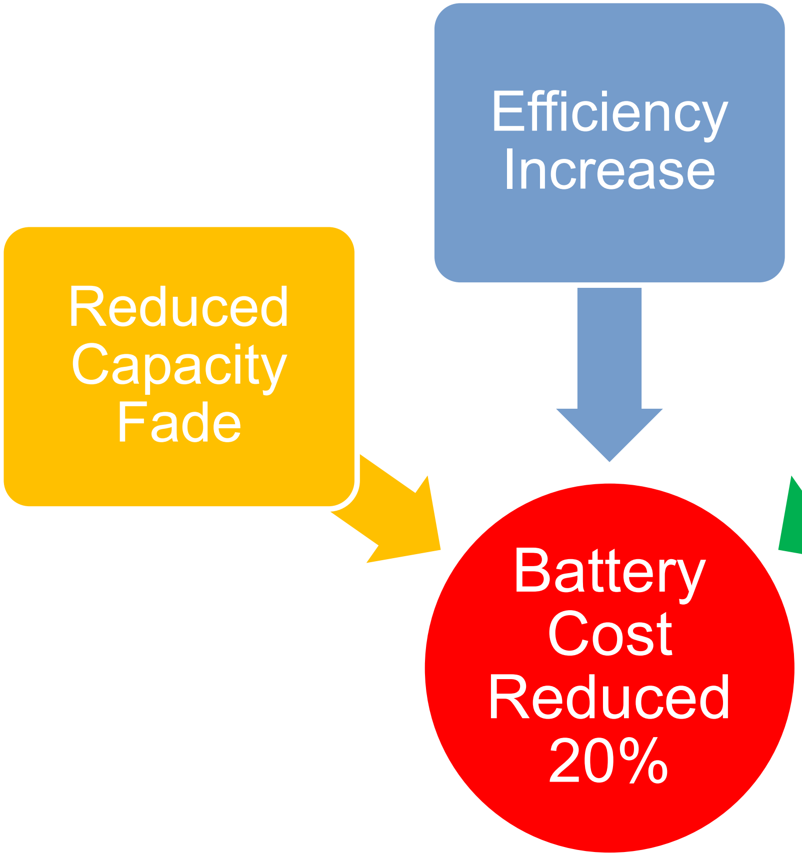
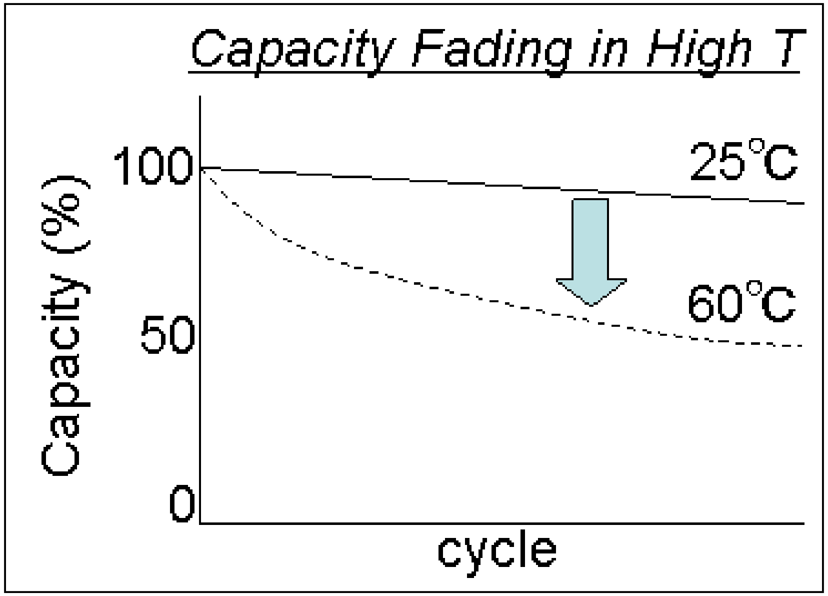
Relevance - Project Objective

Research, development, and demonstration of innovative thermal management concepts that reduce the cell or battery weight, complexity (component count), and/or cost by at least 20%.



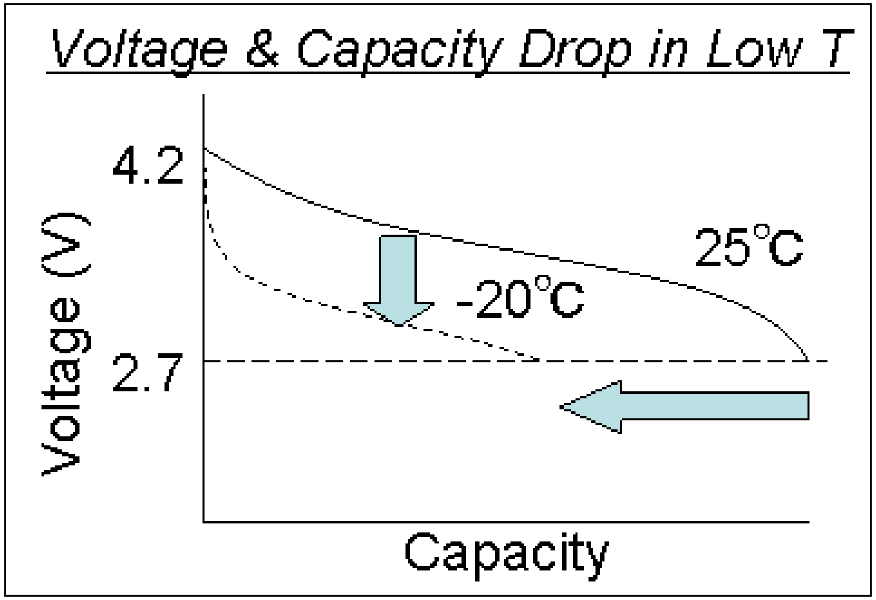
Relevance – Temperature Effect On Batteries

High Temperature Effect



The more time the battery is subjected to high temperatures, greater the capacity is reduced = reduced battery life.

Low Temperature Effect



Battery Voltage and Capacity is reduced at low temperatures = reduced driving range.

Thermal Management Could Enable a Reduction in Battery Size
(Prevent over-size of battery pack to overcome temperature effects)

Approach – Project Strategy

Phase 1
- Study previous research and establish battery simulation model using software that can also simulate thermal systems.

10/2011→01/2013

Phase 2
- Simulation work to evaluate various thermal management concepts and study their effectiveness to enable the reduction of the battery size.

01/2013→01/2014

Phase 3
- Actual bench testing with the thermal management concepts identified in Phase 2. Validation by NREL.

01/2014→09/2015

The thermal system being developed is one that is dedicated to the battery pack which has high efficiency and high reliability for the thermal needs of the battery pack to enable the battery pack size reduction.

Milestones

	Date		Status
Phase I	4/30/2012	Milestone 1: Testing Conditions for Simulation and Bench for Entire Project	Complete
	5/16/2012	Milestone 2: Thermal Characteristics of Battery Cells / Modules	Complete
	1/15/2013	Milestone 3, Budget Period 1 Judgment: Simulation Complete: Does it Match Vehicle Test Data? (Yes/No)	Complete
Phase II	4/11/2013	Milestone 4: Heat Pump System Simulation Results	Complete
	7/10/2013	Milestone 5: Cascade Compressor Heat Pump Simulation Results	Complete
	02/10/2014	Milestone 6: PCM Simulation Results	Complete
	03/12/2014	Milestone 7: Vapor Compression Cycle with PTC Heater Simulation Results	Complete
	5/1/2014	Milestone 8, Budget Period 2 Judgment: System Design Complete: Can the Project Objective be Achieved? (Yes/No)	Complete
Phase III	09/30/2014	Milestone 9: Prototype Parts Completed	Complete
	02/27/2015	Milestone 10: Cooling System Testing Complete	Complete
	3/06/2015	Milestone 11: Heating System Testing Complete	Complete
	3/20/2015	MILESTONE 12: Initial Bench Testing Complete: Are Project Objectives Achieved? (Yes/No)	Complete
	9/2015	MILESTONE 13: Budget Period 3 Judgment: Final Bench Testing Complete: Are Project Objectives Achieved? (Yes/No)	On Track

All milestones are completed except for final testing at NREL.

Approach / Strategy

Phase I					Phase II				Phase III				1 Year No Cost Extension		
2011	2012				2013				2014				2015		
4th Qtr	1st Qtr	2nd Qtr	3rd Qtr	4th Qtr	1st Qtr	2nd Qtr	3rd Qtr	4th Qtr	1st Qtr	2nd Qtr	3rd Qtr	4th Qtr	1st Qtr	2nd Qtr	3rd Qtr

Create Battery Simulation Model

- Battery Cell Simulation with support from NREL who provided cell thermal characteristics
- Battery model correlated to actual vehicle data from FCA US

Create Thermal System Models and Study Effect

- Research high efficiency vapor-compression cycles to be used for active battery thermal management.
- Passive thermal management technologies were also studied.
- NREL provided the battery life model and help with incorporating into the rest of the model

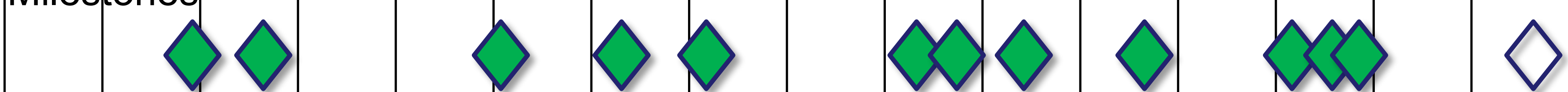
Bench Testing to Validate Models

- Bench testing actual vehicle battery pack with actual thermal system.
- Check various real world drive cycle conditions used in the industry, compare to simulation.
- FCA US help to set up battery pack for bench testing.

Testing at NREL

- Bench testing to validate testing at DENSO and further study benefits and uses of the thermal system.

Milestones



= Completed = Not Completed

The approach has three phases which includes building a battery model, thermal system simulation and doing actual bench testing. Final step is validation at NREL.

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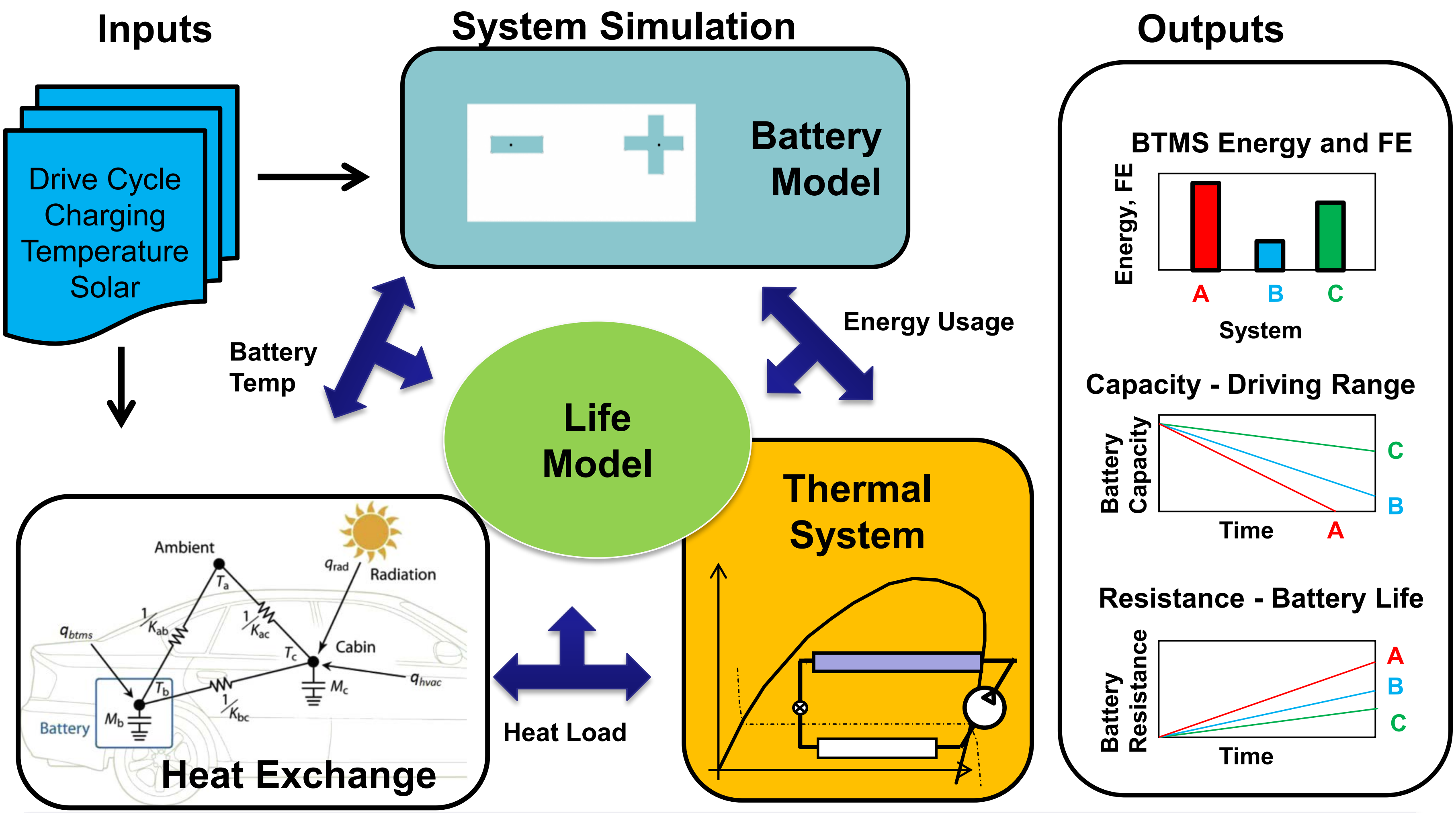
Approach - Battery Simulation Model



Model vehicle usage, ambient, battery heat generation and thermal system to determine battery life, fuel economy and energy effects of thermal system.

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Approach – Climates and Driving Habits

5 Climates

Seattle

New York

Los Angeles

Minneapolis

Miami

X

5 Drive Habits

Combinations of:

HFET, US06, UDDS

Distance Driven

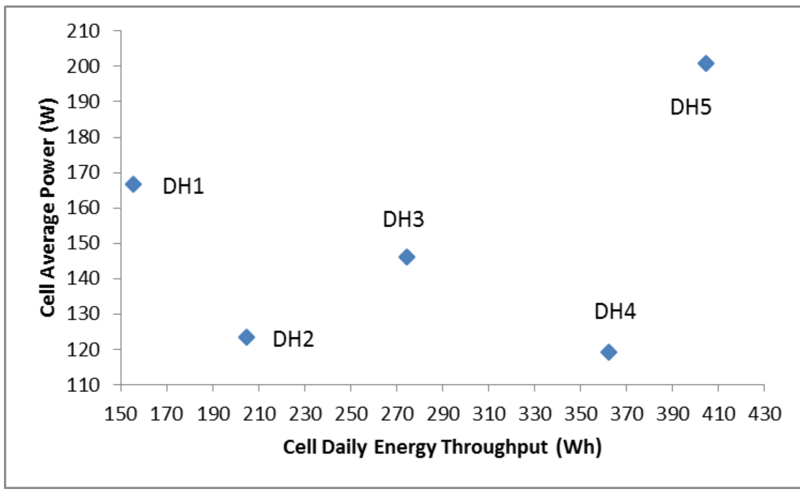
Idling time

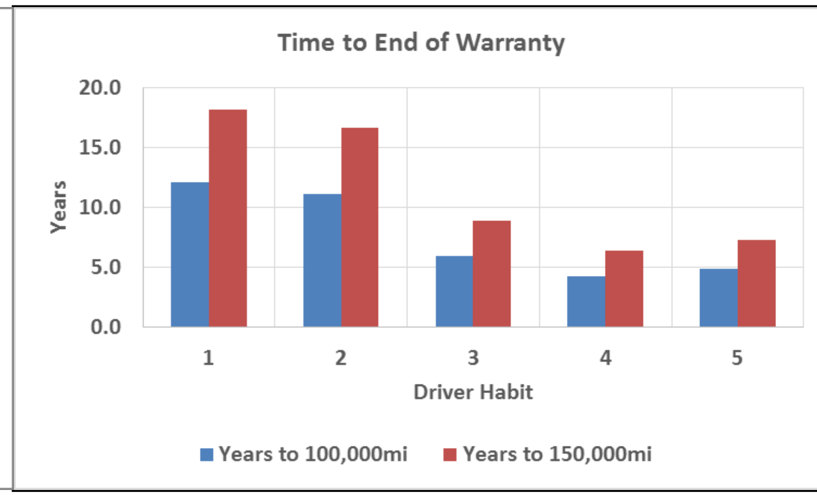
Departure times

=

25 Total Scenarios

Cover wide spectrum of usage cases

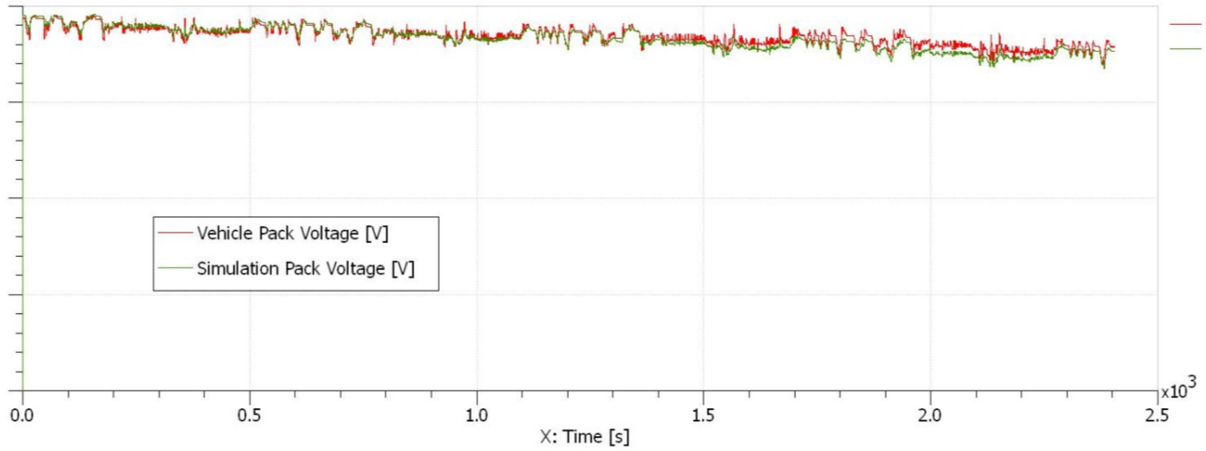


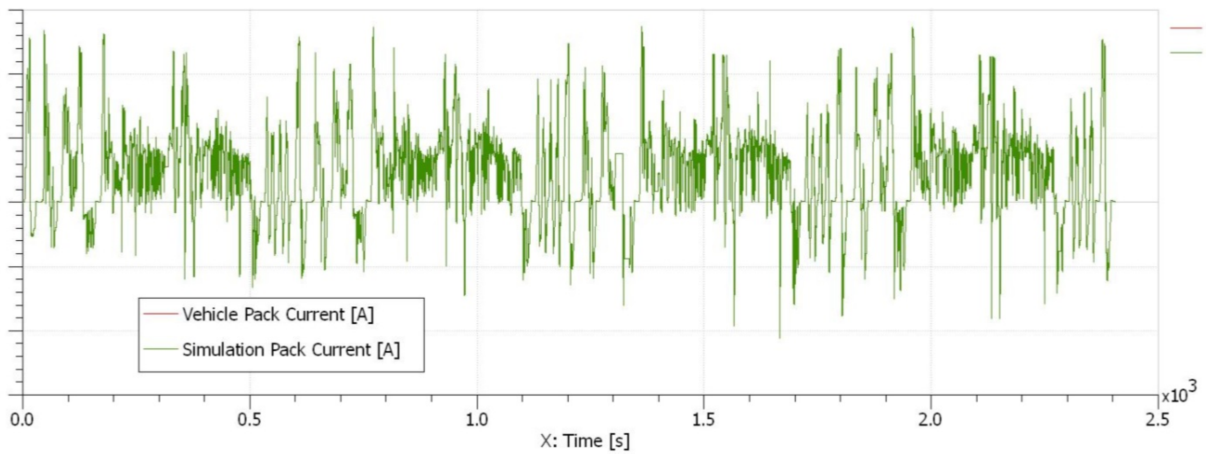


Hottest = Miami, aggressive city driving during hottest part of day
Coldest = Minneapolis, short driving during cooler parts of day
Mild = Seattle, moderate driving pattern and mild climate

Examine battery life and energy savings at various usage scenarios.

Technical Accomplishments – Phase I





Conclusion for Phase I: The battery voltage and current simulation results match the vehicle test data.

Technical Accomplishments: Milestones 4 → 8
Thermal Systems Studied

Milestone 4 & 5 & 7: Heat Pump simulation (Define what heat pump systems are)

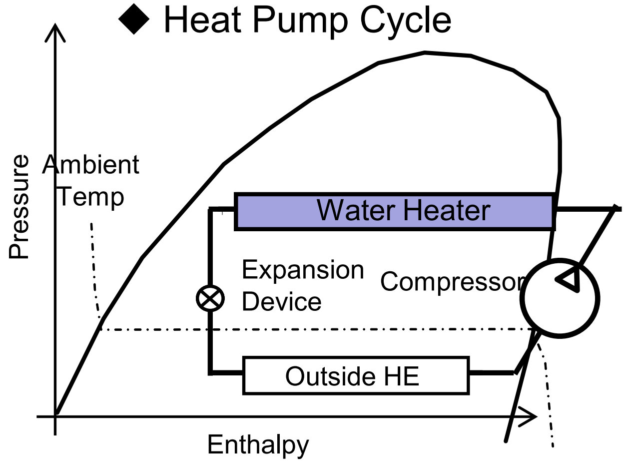
System under consideration:
- Battery electric vehicle
- Liquid cooling / heating
- Pack mounted to floor

PTC, HP and GIHP Systems will be evaluated in the simulation model.

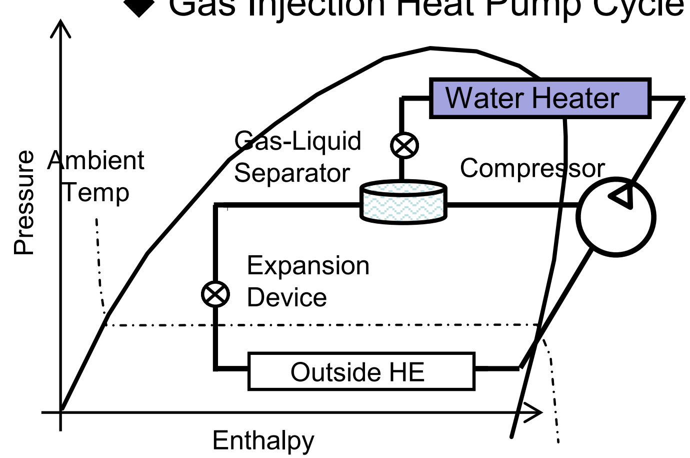
Cooling System	Heating System	Comment
Chiller	Water PTC	Base System
Chiller	HP	Improve COP
Chiller	GIHP	Improve low ambient temperature performance
Chiller + PCM	HP	Add passive heat adsorption

PTC = Positive Temperature Coefficient (resistance heater)
(GI) HP = vapor compression (Gas Injection) Heat Pump
PCM = Phase Change Material (latent heat of fusion)

◆ Heat Pump Cycle



◆ Gas Injection Heat Pump Cycle



Gas injection heat pump provides greater performance at cold ambient.

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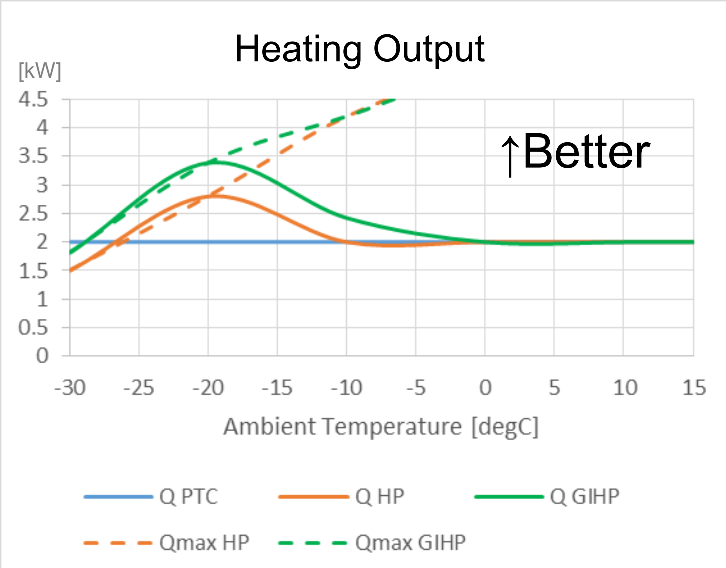
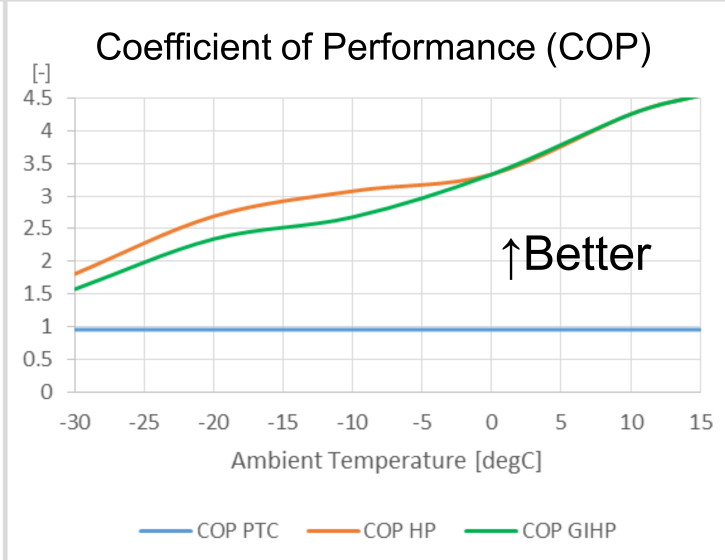
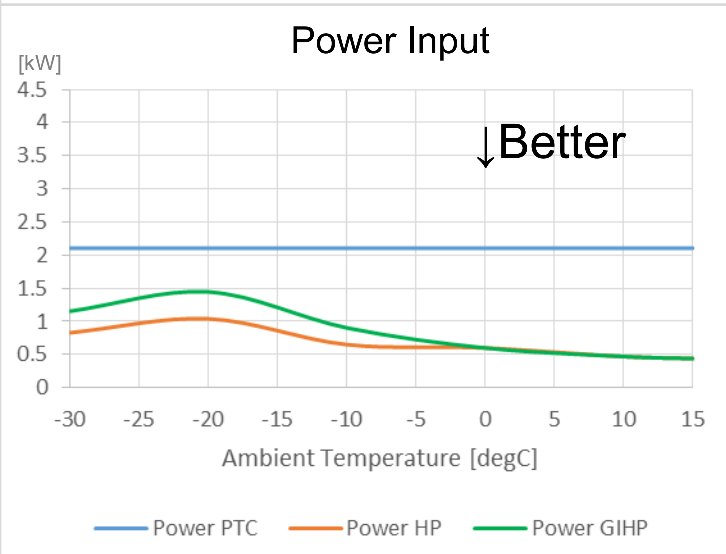
Technical Accomplishments – Phase II

Milestone 4 & 5 & 7: Heat Pump simulation results (Warming the battery from -30°C Soak)





$$\text{COP} = \frac{\text{Heating Output}}{\text{Power Input}}$$



Notes:
- Base system (PTC) heating output is assumed 2kW
- PTC heater COP is assumed 1. (actual is slightly less than 1)
- Refrigerant for heat pump is R-134a
- Heat pump compressor speed is limited to keep 2kW output (same as PTC).

Heat pump has higher efficiency (coefficient of performance) than PTC heater. Heat pump saves energy during heating.
For cooling, the 3 systems use the same energy.

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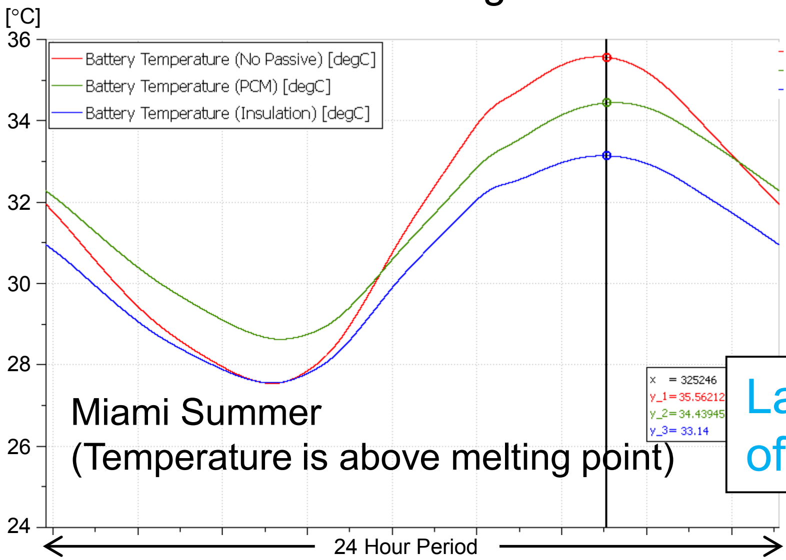
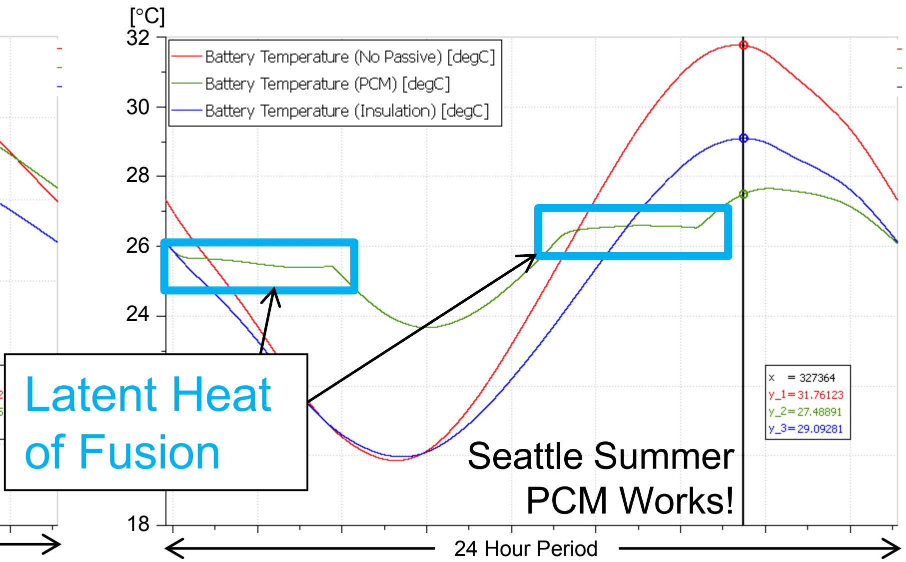
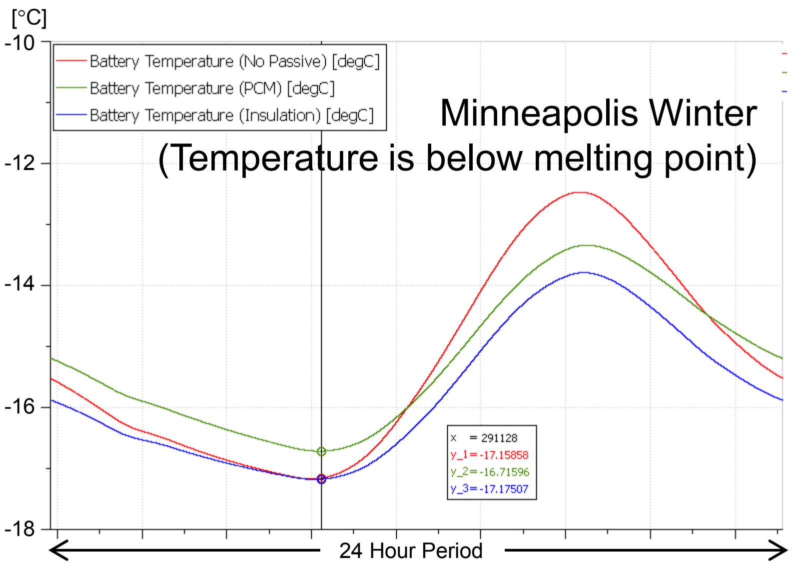
Technical Accomplishments – Phase II

Milestone 6: Phase Change Material Simulation Results When Vehicle Is Parked







Notes:

- PCM Melt point is 26°C
- Used to reduce battery temperature cycling from ambient temperature swings during the day.
- Car is parked most of its life, idea was PCM could help increase battery life (reduce temperature spikes) without using battery power.

PCM is effective in mild ambient, however the added thermal mass requires more energy to be used to actively warm or cool the battery, therefore it was not included in the final system. Adding insulation to the battery pack helps in all conditions, and doesn't effect active cool down or warm up as much.

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Technical Accomplishments: Milestones 4 → 8
Thermal Systems Studied

Milestone 4 & 5 & 7: Heat Pump simulation (Define what heat pump systems are)

“NEW” System →

Cooling System	Heating System	Comment
Chiller	Water PTC	Base System
Chiller	HP	Improve COP
Chiller	GIHP	Improve low ambient temperature performance
Chiller + PCM	HP	Add passive heat adsorption

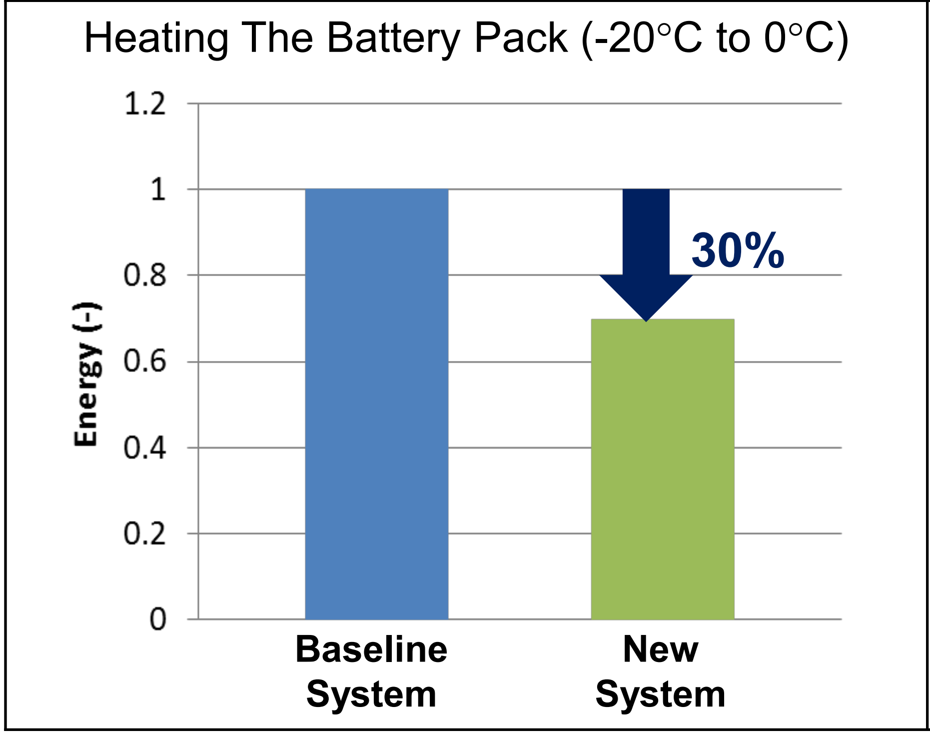
Because of increased performance at cold temperatures and energy savings, Gas Injection heat pump system was used for further analysis.

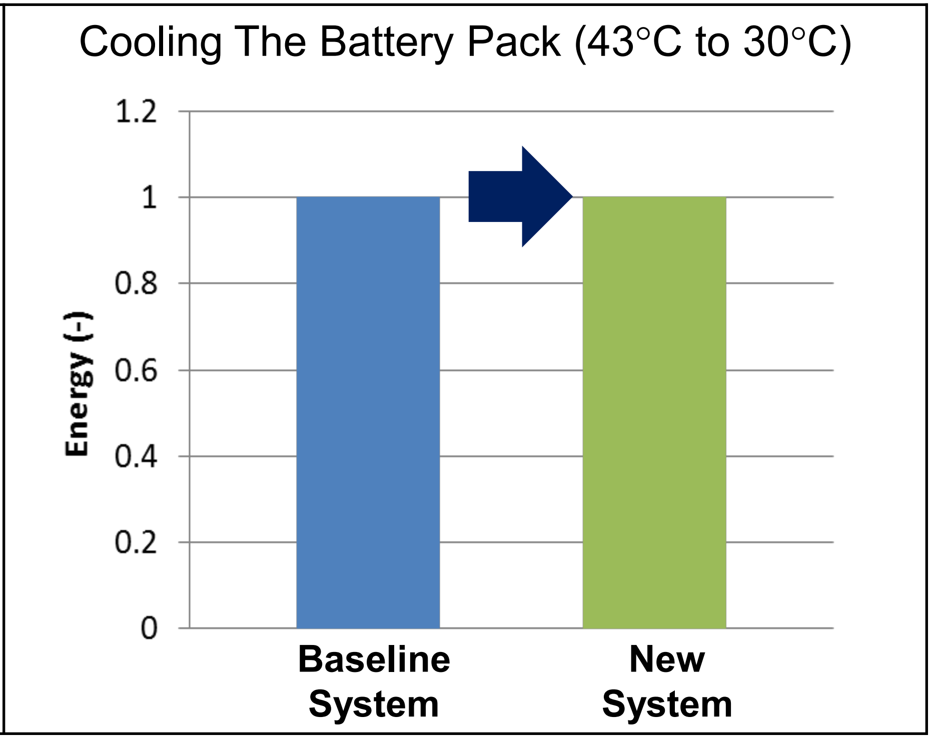
Technical Accomplishments – Phase II

Milestone: 8

Simulation Results using New System (GIHP)

Using the thermal system to warm or heat the battery after the entire system and battery pack are soaked to -20°C or 43°C.





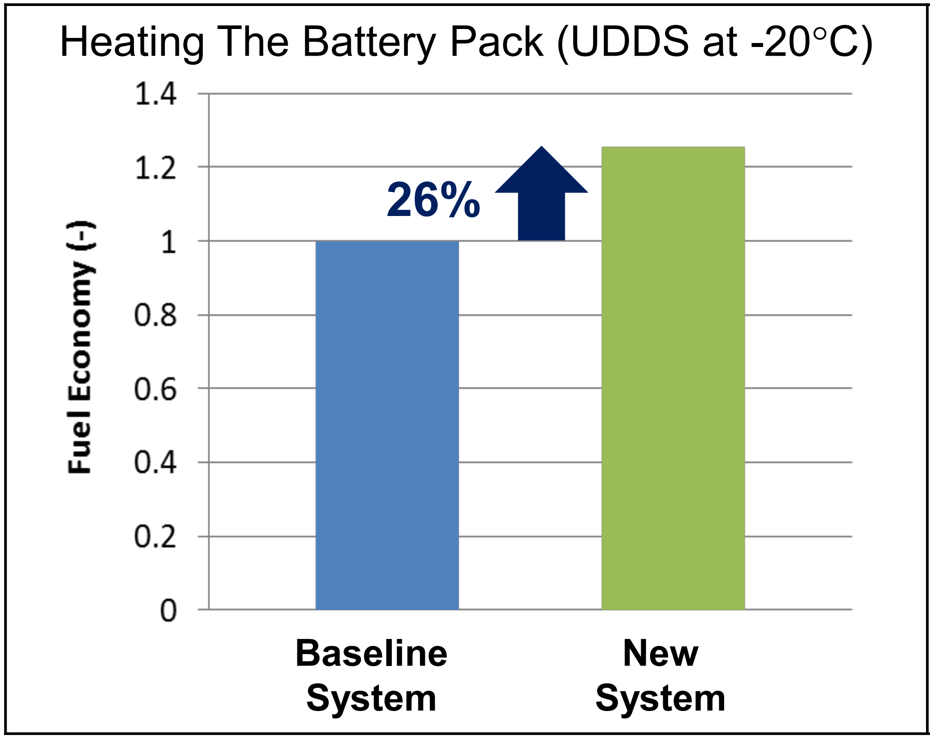
The new system uses 30% less energy than base system to heat the battery pack from -20°C to 0°C.

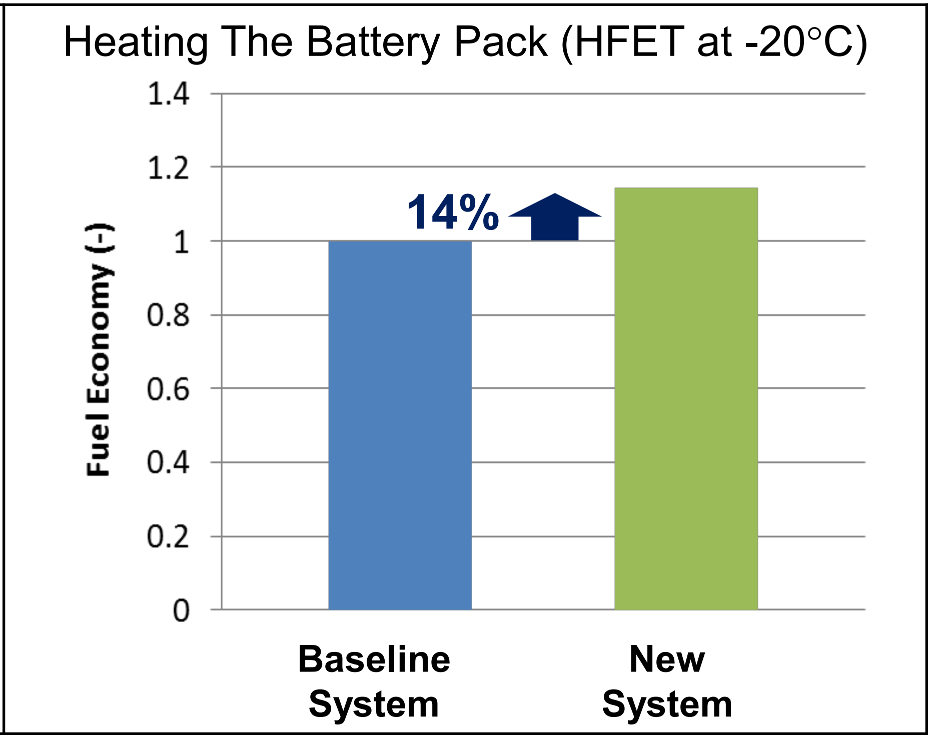
Technical Accomplishments – Phase II

Milestone: 8

Simulation Results using New System (GIHP)

Effect on Fuel Economy using the thermal system to warm the battery pack during UDDS and HFET drive cycles.



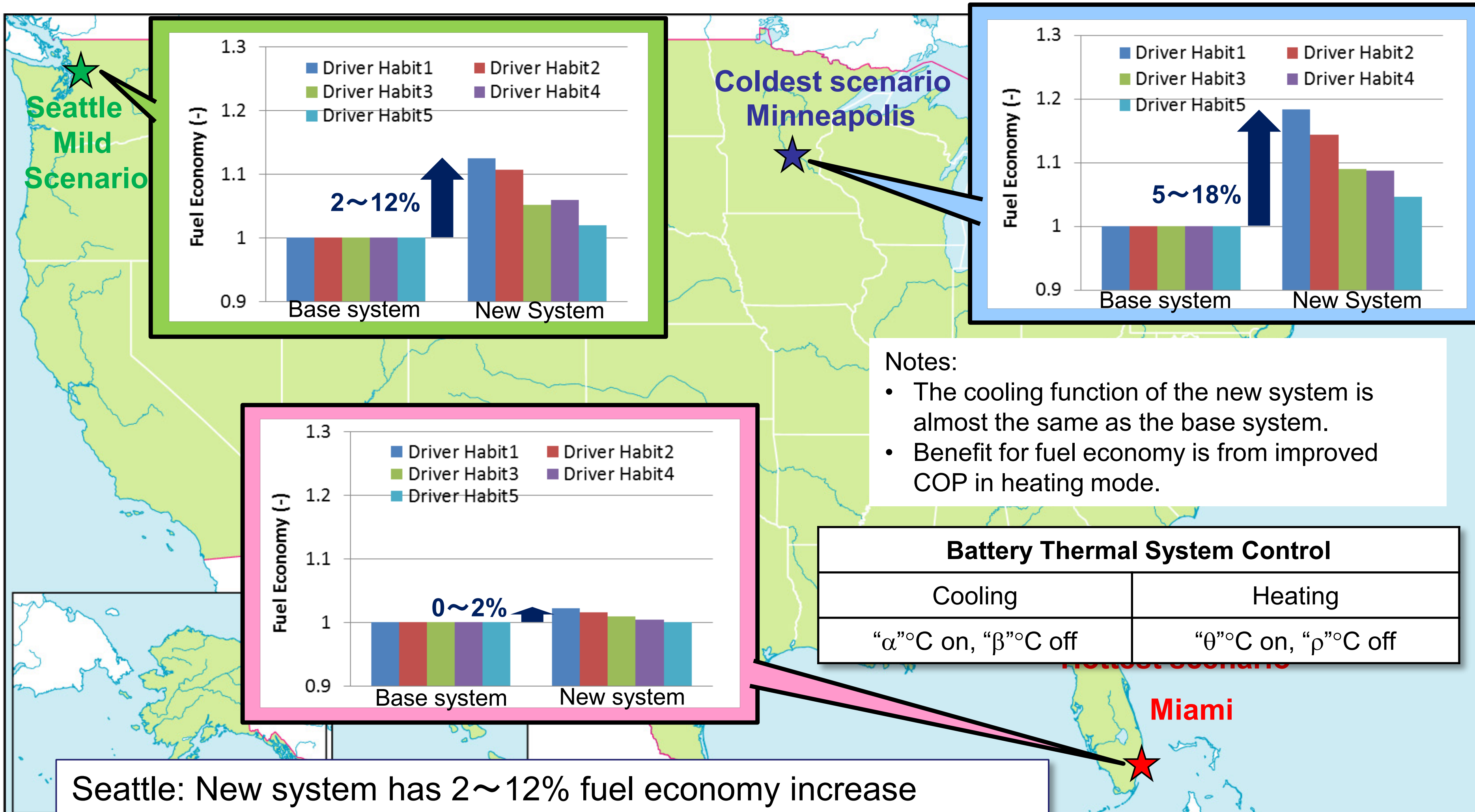


Because highway driving has constant discharge of the battery, the battery generates its own heat and requires less active heating.

The new system has a 26% FE improvement for UDDS (City) and 14% FE improvement at HFET (Highway).

Technical Accomplishments – Phase II

Milestone 8: Results of Simulation (Effect on Driving Range In Various Scenarios)



Notes:
- The cooling function of the new system is almost the same as the base system.
- Benefit for fuel economy is from improved COP in heating mode.

Battery Thermal System Control	
Cooling	Heating
“α”°C on, “β”°C off	“θ”°C on, “ρ”°C off

Seattle: New system has 2～12% fuel economy increase
Minneapolis: New system is 5～18% fuel economy increase
Miami: Almost no effect (heating system is hardly used)

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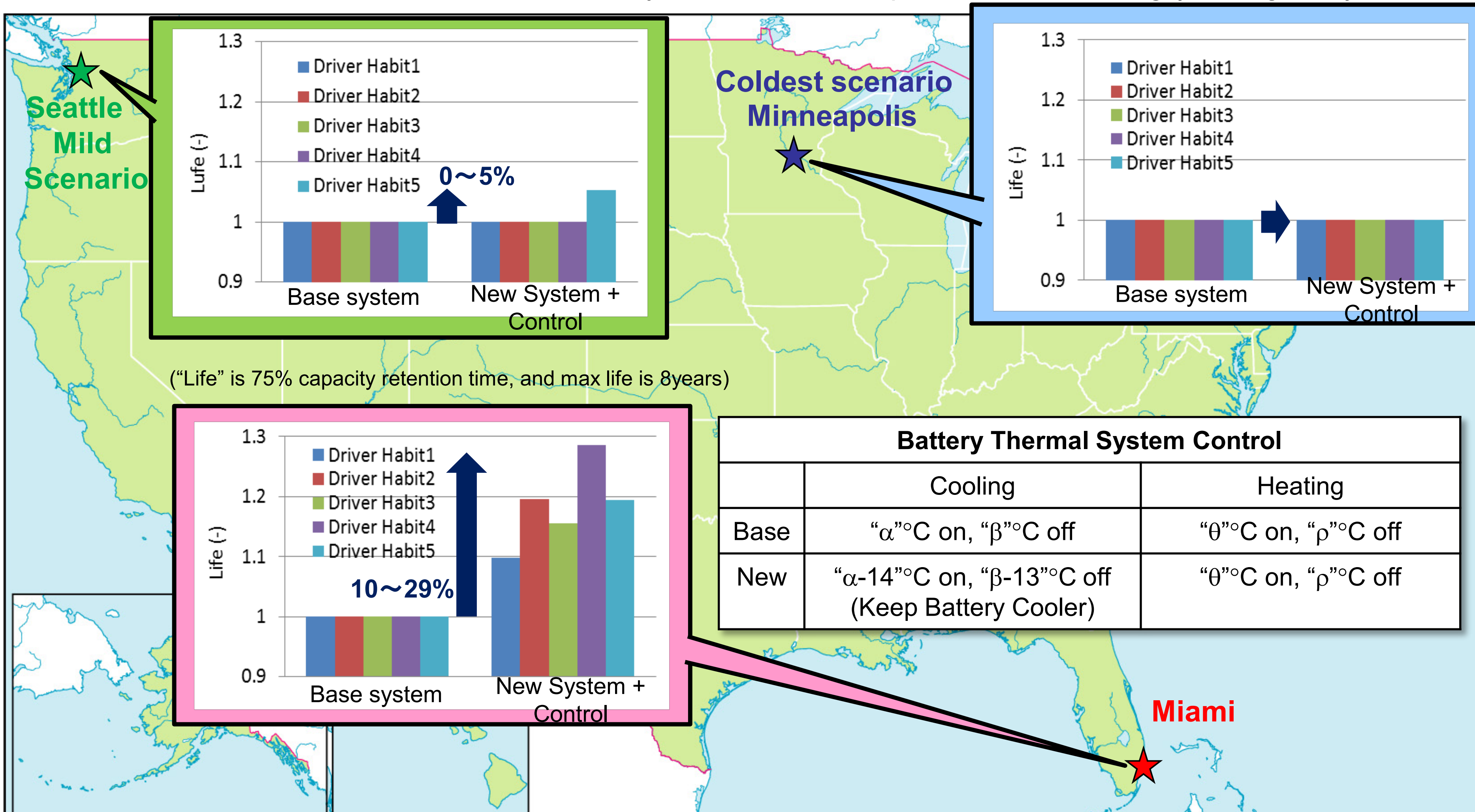
Technical Accomplishments – Phase II

Milestone: 8 Simulation Results New Thermal System Control Temperatures for Cooling **(Battery Life)**



Battery Thermal System Control

	Cooling	Heating
Base	"α"°C on, "β"°C off	"θ"°C on, "ρ"°C off
New	"α-14"°C on, "β-13"°C off (Keep Battery Cooler)	"θ"°C on, "ρ"°C off

Keeping the battery cooler in hot ambient like Miami can increase the life 10-29%. (Ave. 20%)

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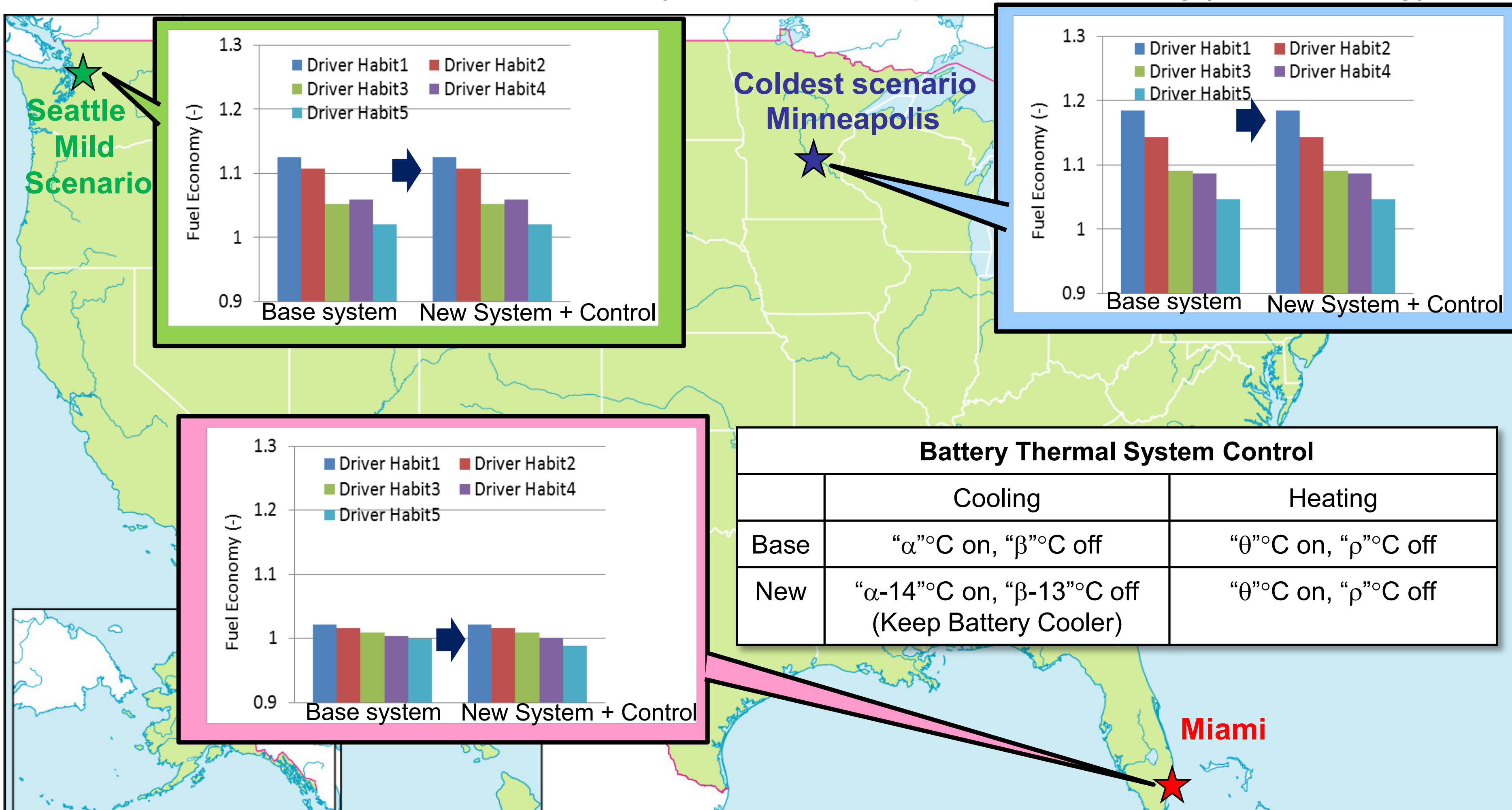
Technical Accomplishments – Phase II

Milestone: 8 Simulation Results New Thermal System Control Temperatures for Cooling **(Fuel Economy)**



Battery Thermal System Control		
	Cooling	Heating
Base	“α”°C on, “β”°C off	“θ”°C on, “ρ”°C off
New	“α-14”°C on, “β-13”°C off (Keep Battery Cooler)	“θ”°C on, “ρ”°C off

More aggressive thermal control has little effect on fuel economy, but previous slide shows big improvement in battery life… But what does this mean for battery capacity reduction?

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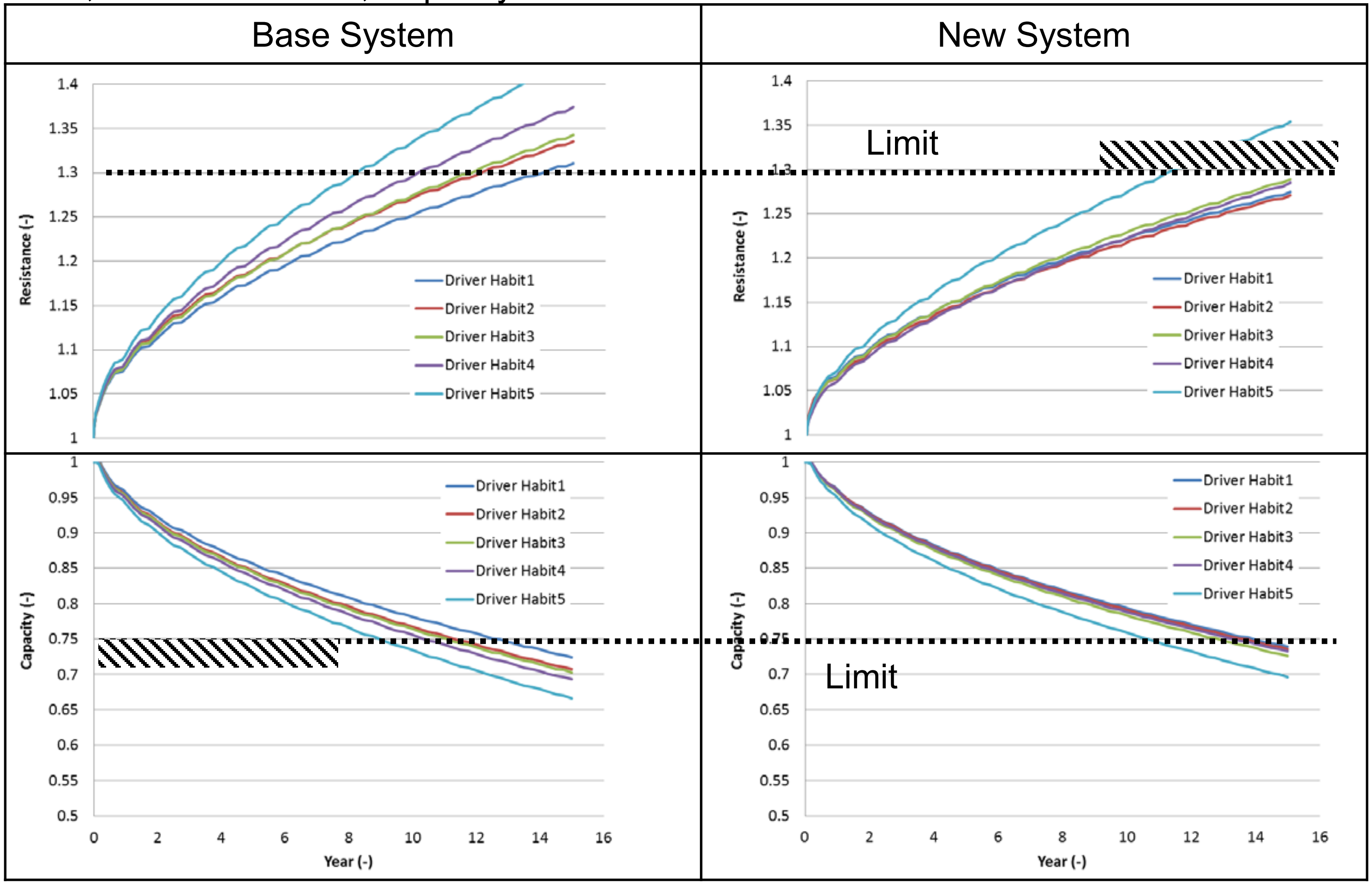
Technical Accomplishments – Phase II

How much battery capacity can be reduced with new cooling system?
Study Miami which had the largest increase in battery life.
Target 8 years life, Resistance ≤ 1.3, Capacity ≥0.75



Now check how much capacity can be reduced but satisfy ≥0.75 at 8 years.

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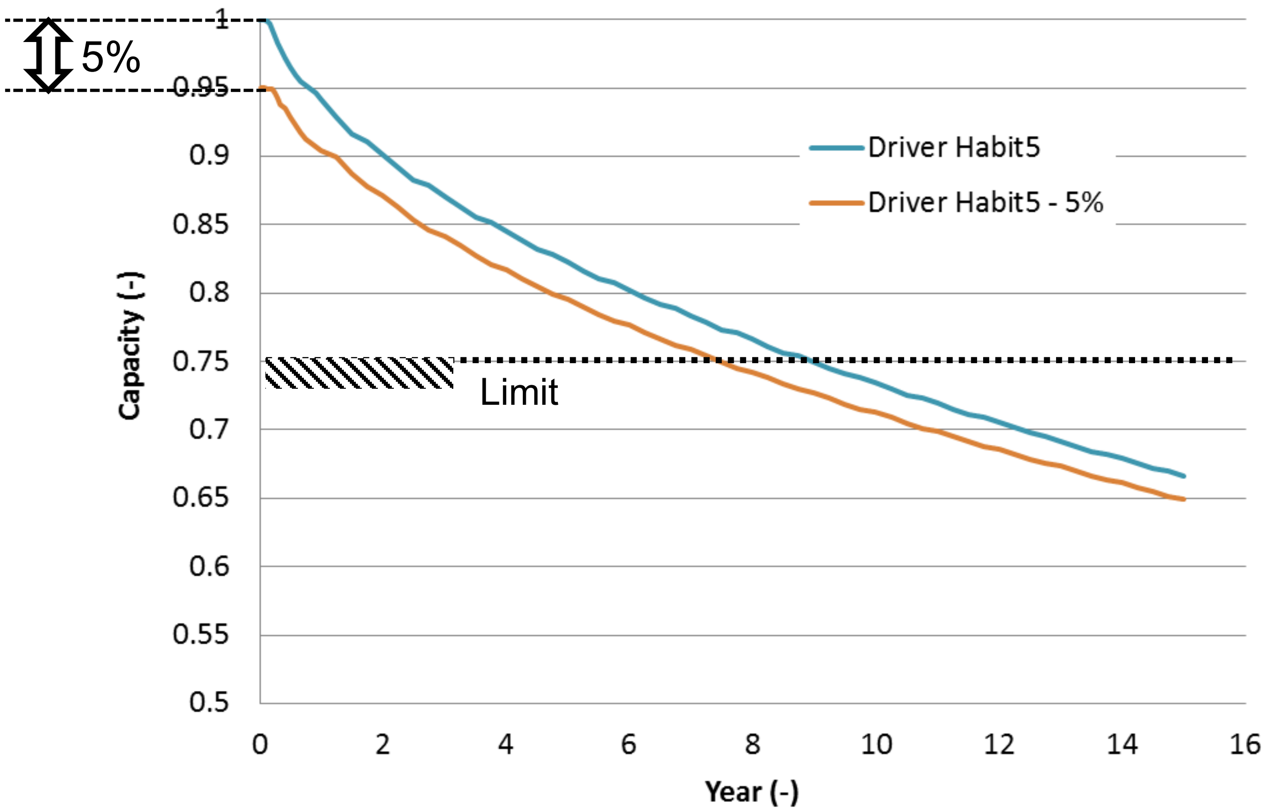
Technical Accomplishments – Phase II

New System, Miami, Drive Habit 5 (worst case): Study how much capacity can be reduced and keep minimum life.



Battery capacity can be reduced 5% and still satisfy ≥0.75 at 8 years.

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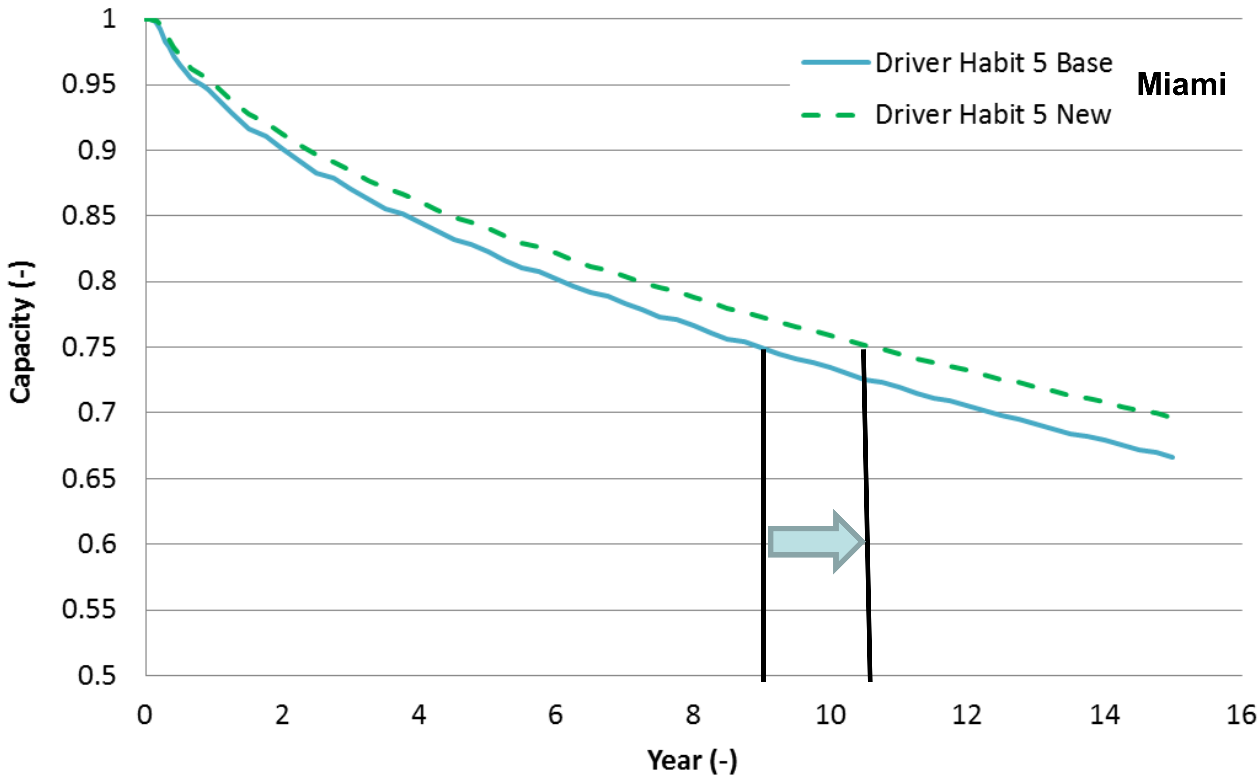
Technical Accomplishments – Phase II

Another way to look at it: Study how much battery life can be increased.



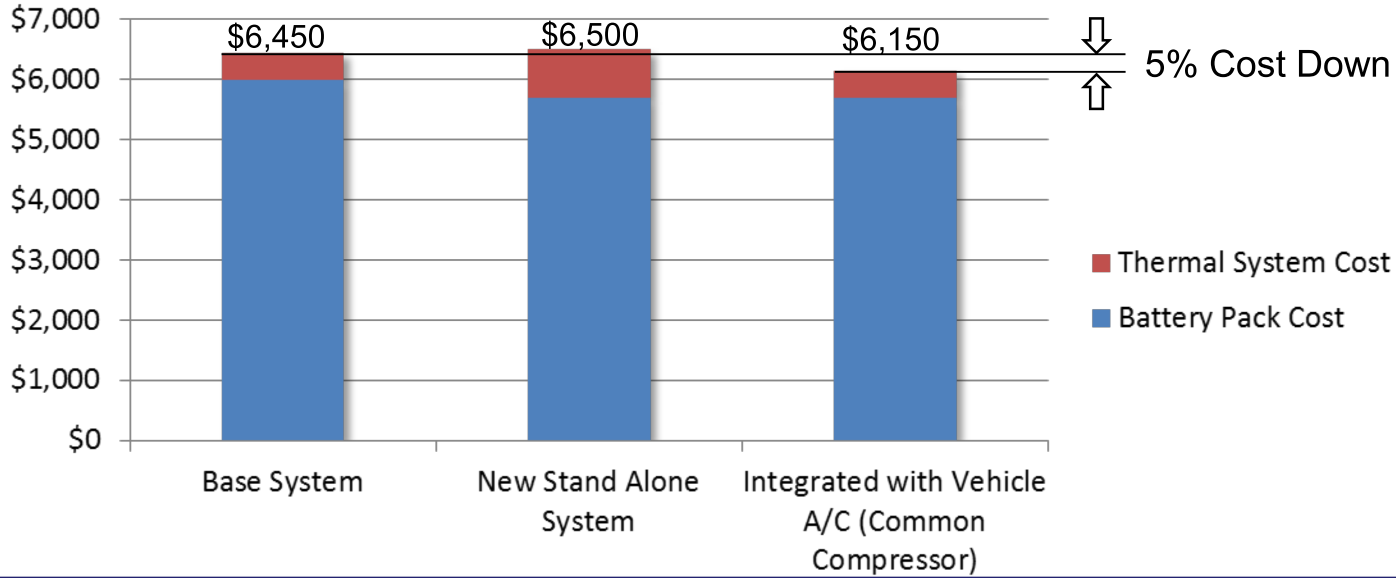
Battery life could be extended ~2 years by keeping the same beginning of life capacity.

Technical Accomplishments – Phase II

Cost Analysis

Assumptions	
Baseline Battery Pack Size	24 kWh
New Battery Pack Size (5% Downsize)	22.8 kWh
Battery Pack Cost (based on industry data)	$250 / kWh
Base Thermal System Cost (chiller + PTC Heater)*	$450
Stand Alone System Cost*	$800
System Cost Integrated into Vehicle A/C*	$450

* These costs are only engineering estimates for a rough cost image.

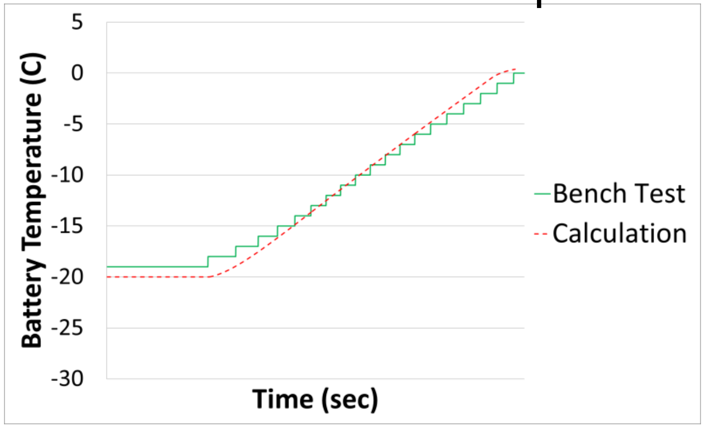


Thermal system with new temperature controls must be integrated with vehicle A/C and use a common compressor to realize an overall cost savings.

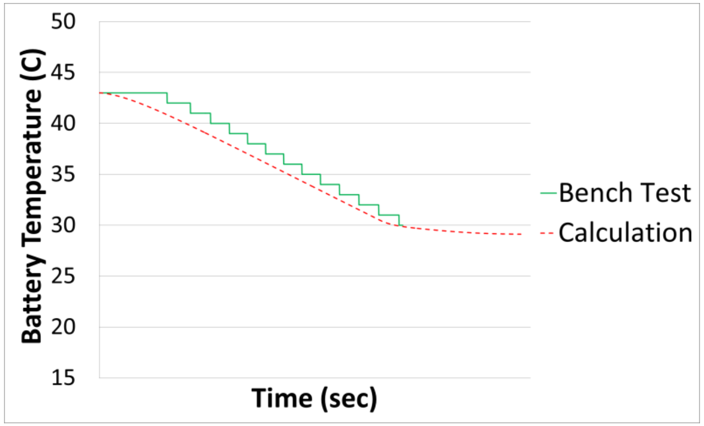
Technical Accomplishments – Phase III

Compare Simulation (calculation) to actual Bench Test Results

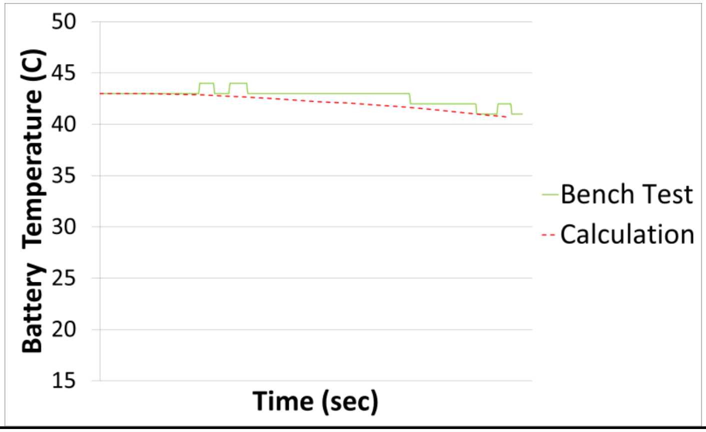
-20°C → 0°C Warm Up Test



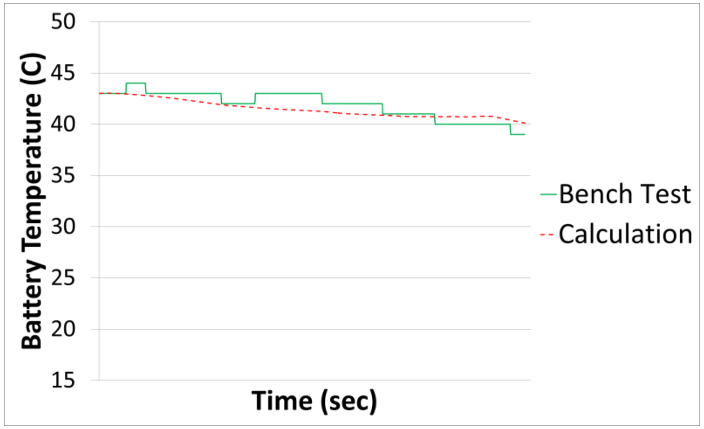
43°C → 30°C Cool Down Test



US06 Drive Cycle after 43°C Soak



Davis Dam Test After 43°C Soak



Simulation matches actual bench test results: Results of simulation can be trusted!

Response to AMR 2014 Reviewer Comments

Comment 1: The reviewer noted a lack of adequate fidelity for the battery simulation model for performance and degradation (first-principles) due to its complexity and specificity for the battery chemistry.

Response 1: It is true that the battery model is not as complex as other models, but for this project it's simulation time is fast to evaluate A to B evaluation of various thermal systems.

Comment 2: The reviewer commented that with the simulation tool developed here it is probably useful to study other thermal management schemes currently being used in EV batteries for a comparative assessment of the cost and efficacy of the selected thermal management methods.

Response 2: The simulation tool can be adopted to other systems such as active air cooling or direct refrigerant cooling, but examining all types was too much and it was decided to be outside the scope and we only examined the FCA US F500EV system. But the results could be applied to other methods.

Comment 3: The the reviewer said resources are adequate perhaps even slightly excessive for the scope of the project.

Response 3: We recognized this which is why actual costs to DOE are under the budgeted amount.

Collaborations

National Renewable Energy Laboratory :

- During FY12, NREL performed testing and provided data for battery cell characteristics which were used in the battery model. NREL also gave guidance for developing the model.
- During FY13, NREL provided the battery life model and help with incorporating it into the rest of the model.
- During FY14, NREL supported final simulation results, attended bench testing at DENSO, and is planning for bench testing at NREL.
- For FY15, NREL will conduct bench testing of the thermal system at their facility.

FCA US:

- During FY12, FCA US provided target battery temperatures, drive cycle data and testing conditions. Also gave guidance for overall design choices.
- During FY13, FCA US provided user drive profiles and cities of interest. They also provided information on design choices and priorities, which influenced the results. FCA US provided a battery pack for testing in FY14.
- During FY14, FCA US helped to set up the battery pack for bench testing, including using CAN to communicate with the battery and measure internal battery information like SOC, current draw and temperature.

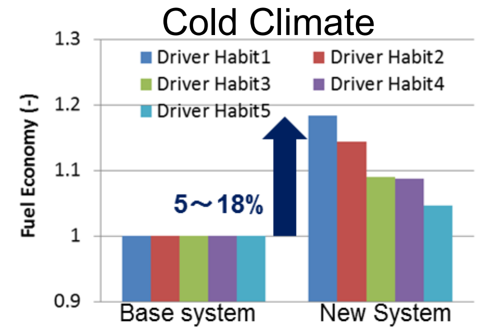
Proposed Future Work

FY15

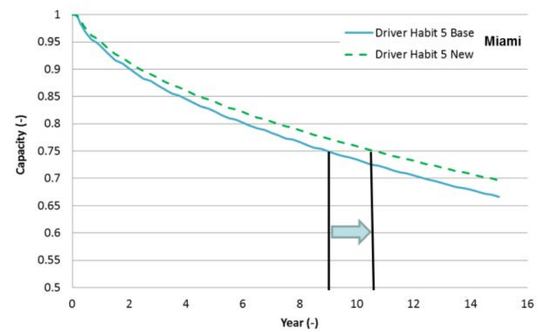
- Validation bench testing at NREL.
- Consider impact on other battery chemistries. (others may be more sensitive to temperature)
- Issue final report.

Summary

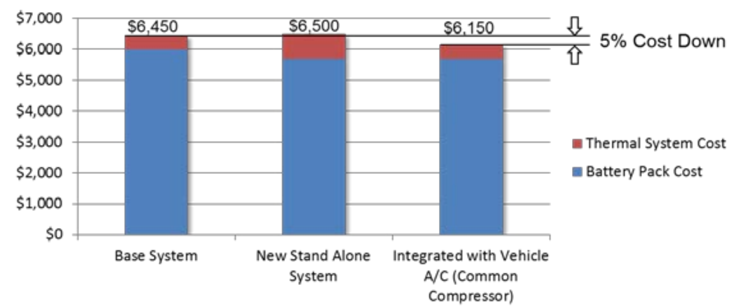
1) Heat pump system improves fuel economy an average 12% in cold climate areas by using less energy to heat the battery compared to PTC heater.



2) By keeping the battery at colder temperatures in hot ambient, total battery capacity can be reduced 5% or battery life can be increased 2 years.



3) By keeping the battery at colder temperatures in hot ambient, total battery and thermal system cost can be reduced 5% if integrated with vehicle cabin A/C system. A stand alone system is not cost effective.



New system and thermal controls can provide 12% fuel economy improvement in cold climate and increase battery life 2 years or and reduce overall battery cost by 5%.

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